



[10191/4133]

## METHOD AND MICROMECHANICAL COMPONENT

### Field Of The Invention

The present invention is based on a method and a micromechanical component.

### Background Information

- 5 Freestanding micro-structures in surface micromechanics usually are produced with the aid of sacrificial-layer technology. To this end a sacrificial layer is produced on a substrate such as silicon, and possibly patterned. Usable as sacrificial layer is silicon dioxide, for example. A functional layer is applied on this sacrificial layer and patterned as well. Polycrystalline silicon or otherwise also silicon nitride, for instance, are able to be used as functional layer.
- 10 By dissolving the sacrificial layer, for example by dry-etching, gas-phase etching or by wet-chemical etching, the functional layer is detached from the substrate, so that it becomes free-standing. It is suspended from the substrate at one or several locations and may bend or vibrate, for example. Uses for such self-supporting structures are, for instance, micro-bars at whose end the tip of a scanning microscope (atomic force microscope AFM, scanning
- 15 tunneling microscope STC and the like) is situated for the scanning of surfaces. Other applications for such micromechanical structures are sensors which determine chemical substance concentrations on the basis of the absorption of molecules on a micro-bar via its deformation, and may thus also be called "artificial noses". Additional applications are micro-bars, which are utilized as actuators for optical micro-mirrors, such micro-mirrors being
- 20 employed as optical switches, filter or the like. Further application possibilities are micro-grippers etc.

In addition, it is known to produce porous silicon. To this end, the semiconductor substrate, which is provided in the form of silicon substrate, in particular, is provided with a large

25 number of pores with the aid of an electro-chemical wet-etching method in a fluoride-containing solution, so that porous silicon is formed in the region of the substrate in which the pores are located.

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### Summary Of The Invention

In contrast to the related art, the method and the micromechanical component according to the present invention, have the advantage of using as sacrificial layer a region of porous silicon or a region of porous substrate material. On the one hand, it is then possible to apply the functional layer on the silicon substrate first and to implement undercut-type etching of the substrate by electrochemical wet-etching to make it porous in a subsequent step. In a final processing step, the porous substrate region is dissolved in diluted alkaline solution, thereby exposing the functional layer from below. This procedure is shown in Figures 3 and 4, in particular.

However, according to the present invention it is provided, in particular, that the porous region on the surface of the silicon substrate be produced in a first step by electrochemical wet-etching of silicon in a fluoride-containing solution, and that the functional layer, made of silicon, for example, be applied in a second step. In addition to the functional layer, other layers such as silicon nitride, metal or the like also may optionally be applied on the substrate and patterned so as to produce prestressing in the functional layer, for example, or also in order to integrate actuator or sensor elements in the functional layer or to contact these elements. Furthermore, as an option, the porous layer may also be oxidized after it has been produced. As illustrated in Figures 1 and 2, the functional layer is patterned above the porous region so as to give it the desired form, i.e., it forms a bar, for example, which, once it has been exposed, is directly or indirectly connected to the substrate at defined locations only. In a third step, the sacrificial layer is dissolved or relocated. Dissolution or etch removal of the porous layer may be accomplished in diluted KOH solution, for instance, or also TMAH solution (tetra-methyl ammonium hydroxide)  $(CH_3)_4NOH$ . As an alternative, in particular in the case of oxidized porous silicon, the etch removal of the porous region may be carried out in hydrofluoric acid (HF) or BHF (buffered HF, buffered hydrofluoric acid) or by gas-phase etching in a fluoride-containing environment.

The advantage of using porous silicon as sacrificial layer as compared to the use of silicon dioxide as sacrificial layer is that porous silicon allows considerably deeper etching than would be possible when using thermal silicon oxide, due to the producible thickness of this material. Furthermore, it is possible, in particular if the porous region, i.e., the sacrificial layer, is produced earlier than the functional layer, that a wet-chemical application will no longer be required after formation of the functional layer. Moreover, the procedure described

in Figures 3 and 4, in which the functional layer is formed first and the porous silicon region afterwards, requires a further separating layer, such as silicon dioxide, from the functional layer, which is not the case in the sequence described in Figures 1 and 2. In contrast, the selectivity in rendering silicon porous by an electrochemical process may also be managed by local doping as it is commonly done in an integrated semiconductor process as it is. This makes it easier to embed the process of the present invention in the manufacturing sequence of integrated electronic circuits with a micromechanical component, in particular if the functional layer is produced after the porous region has been created, without this requiring special wafers such as SOI wafers (silicon on insulator).

It is particularly advantageous that the porous region is produced first and the functional layer later, since this simplifies the management of the manufacturing process considerably and, furthermore, no longer requires any wet-chemical step following production of the functional layer, advantageous structural effects being derived in addition. When producing the porous layer after the functional layer, in particular, the problem is encountered that "noses" will form during production of the porous layer, which constitutes an isotropic process step. Especially at the edge of free-standing structures, such "noses" provide poor definition of their suspension. Moreover, it is advantageous that a doped first region is produced in the substrate in which no pores will form, and that the porous region will be produced subsequently. This allows patterning of the porous region to be carried out in a simple manner. Furthermore, it is advantageous that the porous region is able to be removed below the functional layer by etching in a dry-chemical manner, thereby simplifying the production process of the micromechanical component. It is also advantageous that the porous region has a first porous partial region and a second porous partial region, the second porous partial region having higher porosity, and that a cavity is formed in the region of the second porous partial region by a thermal treatment, a cover layer remaining in the region of the first porous partial region. This allows the functional layer to be exposed later on using a trench-etching method.

#### Brief Description Of The Drawings

Fig. 1 shows a first manufacturing method according to the present invention.

Fig. 2 shows a second manufacturing method according to the present invention.

Fig. 3 shows a third manufacturing method according to the present invention.

Fig. 4 shows a micromechanical component according to the third manufacturing method of the present invention.

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#### Detailed Description

Figure 1, by way of example, illustrates the first manufacturing method according to the present invention for producing a micro-bar for an atomic force microscope (AFM). The atomic force microscope includes a tip, which has been provided with reference numeral 132 in Figures 1c and 1d and is connected to a free-standing micro-bar, which is flexible within certain limits and is able to be moved. However, according to the present invention, it is of course also possible to produce other micromechanical structures on the basis of the method according to the present invention. Pertinent examples are micromechanical sensors such as engine-speed sensors or also linear acceleration sensors, which include masses in the functional layer affixed to spring elements whose deflections are altered as a function of external accelerations or rotational speeds.

Illustrated in Figure 1, in each case in Figures 1a through 1d, are various process stages of the micromechanical component according to the present invention, namely, on the left side, a sectional view through a substrate processed according to the first method of the present invention and, on the right side, a plan view of a substrate processed in this manner. Figure 1a shows a semiconductor substrate 100, which includes doped first regions 102 and is covered by a masking layer 110 in partial areas of its surface. Substrate 100 according to the present invention is, in particular, a positively doped silicon substrate 100 in which local negative dopings have been introduced as doped first regions 102. As an alternative or in addition, substrate 100 is covered by cover layer 110, which is provided as nitride mask ( $\text{Si}_3\text{N}_4$ ), for instance. The covering of substrate 100 defines the areas to be rendered porous. In Figure 1b, semiconductor substrate 100 according to the present invention is shown after a porous layer 106 has been produced. It is obtained by producing electrochemically porous silicon as sacrificial layer 106 in region 106 in a fluoride-containing solution. Typical layer thicknesses of this porous layer or this porous region 106 range between 1  $\mu\text{m}$  and 100  $\mu\text{m}$ . As an option, porous layer 106 or porous region 106 is able to be oxidized in addition. Nitride mask 110 may be removed in the same etching bath.

Figure 1c shows semiconductor substrate 100 of the present invention on which the micromechanical component according to the present invention is visible already. The micromechanical component according to the present invention is characterized by including a functional layer, which has free-standing regions that are able to move, for instance, or may also be heated to specific temperatures. To this end the micromechanical component must be provided at least partially in free-standing form in its functional layer, which is denoted by reference numeral 130 in Figure 1. In the elucidated example, the tip of an atomic force microscope is described as micromechanical component. Functional layer 130, which is made of epitaxial or polycrystalline silicon, for instance, therefore includes a free-standing front region on which tip 132 of the atomic force microscope is situated. This functional layer 130 is produced in such a way that functional layer 130, in particular a crystalline or polycrystalline silicon, is deposited on silicon substrate 100 and, in particular, on region 106 rendered porous. Using other methods known from semiconductor technology, additional layers cooperating with functional layer 130 may be produced. A silicon-nitride layer as patterned region has been provided with reference numeral 140 in Figure 1 by way of example. Furthermore, an aluminum layer, as additional patterned region cooperating with functional layer 130, is deposited on the component in a patterned fashion and denoted by reference numeral 142. Aluminum layer 142 is used, for instance, to supply or shunt signals onto silicon-nitride layer 140, which is utilized for the heating of functional layer 130, for example. According to the present invention, layers 140, 142, which cooperate with functional layer 130, are provided as sensor elements or actuator elements, in particular, which are able to bend the micro-bar in an outward direction, especially with prestressing. Both functional layer 130 and layers 140, 142 cooperating therewith normally are patterned as well according to the present invention in order to give them the desired form.

In a further method step, porous layer 106 or porous region 106 is dissolved and functional layer 130 thereby exposed at least partially. The result of this process is illustrated in Figure 1d. Here, porous region 106 is basically removed completely, which is why porous region 106 is also known as sacrificial layer. This removed region is denoted by reference numeral 108 in Figure 1d. The removal of sacrificial layer 106 exposes functional layer 130. If porous silicon is involved, this removal may be accomplished with the aid of diluted alkaline solution, for example by KOH or TMAH. In the case of oxidized porous silicon, a fluoride-containing solution such as HF or BHF is suitable. In both cases it is also possible to use dry-etching methods such as reactive ion etching on the basis of SF<sub>6</sub> (sulfur hexafluoride). By

dissolution of porous layer 106, which - due to the low wall thickness of the pores - occurs much faster by several orders of magnitude than the etching of an equally thick, solid layer of silicon, functional layer 130 is partially exposed or detached from substrate 100 from underneath, so that it becomes free-standing. Due to suitable prestressing, it is able to bend out of the substrate plane in order to be used as spring bar for the tip of an atomic force microscope. In Figure 1d, this is illustrated by an arrow bearing reference numeral 129.

Figure 2 shows an alternative second manufacturing method according to the present invention. Once again, substrate 100 and first doped regions 102 are provided, which delimit the porous region to be produced at a later stage. According to the present invention, substrate 100 is provided in the second method as well, especially as positively doped silicon substrate. First doped regions 102 are once again provided as regions having local negative doping, too. As an alternative to doped first regions 102 for delimiting the porous region, it is also possible to provide only a nitride mask as cover layer 110, which bears reference numeral 110 in Figure 2 as well. Overall, the region to be rendered porous is defined by doped first region 102 and/or cover 110. In the second manufacturing method, this region to be rendered porous receives a heavy positive doping on its surface down to a depth of a few  $\mu\text{m}$ . This produces the region of substrate 100 bearing reference numeral 103 in Figure 2a, which, as already mentioned, extends into substrate 100 to a depth of just a few  $\mu\text{m}$ . The heavy positive doping of region 103 amounts to  $10^{19} \text{ cm}^{-3}$ , for example. In Figure 2b, substrate 100 according to the present invention is shown following the method step in which the porous region is produced. In the second manufacturing method according to the present invention of the micromechanical component of the present invention, the porous region is not provided in the form of a single uniform region 106 – as shown in Figure 1 -, but the porous region in the second manufacturing method according to the present invention is subdivided into a first porous partial region 103 and a second porous partial region 104. Hereinafter, both partial regions 103, 104 are also jointly referred to as porous region 106. First porous partial region 103 corresponds to the region of the superficial, highly positive doping of silicon substrate 100, which is shown in Figure 2a bearing reference numeral 103 as well. In the method step for producing the semiconductor substrate according to Figure 2b, electrochemically porous silicon as sacrificial layer is produced in a fluoride-containing solution, typical layer thicknesses of entire porous region 106 once again amounting to between 1  $\mu\text{m}$  and several 100  $\mu\text{m}$  in all. Due to the etching characteristics of porous silicon, layer 103 having a higher positive doping, i.e., first porous partial region 103, has lower

porosity than second porous partial region 104, which is located in the region of substrate 100 that has lower positive doping. In addition to the different dopings of substrate regions 103, 104, a similar, or even stronger, effect may also be produced by altering the current intensity or current density during pore formation. The porous silicon exhibits higher porosity in second porous partial region 104 than in first partial region 103. Instead of producing only one highly porous layer in second porous partial region 104 of porous overall region 106, the present invention allows the implementation of electro-polishing of the silicon material in second porous partial region 104 at even higher current intensities, thereby producing a cavity underneath porous layer 103 in first porous partial region 103. However, this is merely an optional part of the second manufacturing method according to the present invention.

According to the present invention, porous layers 103, 104 are able to be oxidized optionally. In the method for producing porous layers 103, 104 nitride mask 110 as cover layer 110 may be removed, too. In the second manufacturing method according to the present invention, the porous partial layers of the porous layer are relocated at a high temperature of approximately 900°C to 1100°C under a hydrogen atmosphere at atmospheric pressure, such relocation taking place after the pores have been produced. This removes the highly porous layer in second porous partial region 104, if it still exists, i.e., if no electro-polishing step has been carried out. The region of second porous partial layer 104 transforms itself into a hollow space or a cavity during this relocation and has been provided with reference numeral 107 in Figure 2c. The upper, less porous or lower-porosity layer 104, which is also referred to as first porous partial region 103, is transformed into a cover layer 105 during this relocation. According to the present invention, the pores of cover layer 105 are largely closed, in particular.

After relocation to produce cavity 107, functional layer 130 of the present invention, together with its auxiliary layers or with layers 140, 142 cooperating with the functional layer, is deposited and patterned in a manner similar to that described in Figure 1. Functional layer 130 once again is provided either in the form of an epitaxial layer or a polycrystalline layer, in particular made from silicon. Functional layer 130, or layers 140, 142 cooperating therewith, are patterned in a manner similar to that described in Figure 1, in this way giving them the desired form. This may preferably be accomplished with the aid of a dry-etching method such as reactive ion etching on the basis of SF<sub>6</sub>. By etching, especially by trench etching, of the functional layer and cover layer 105, functional layer 130 is removed from substrate 100 and thus exposed, so that it becomes free-standing. As a result of suitable

prestressing of functional layer 130, it is able to bend out of the substrate plane so as to be used as spring bar for an atomic force microscope tip.

A further exemplary embodiment according to the present invention is represented in Figure

3. In contrast to the two first manufacturing methods according to the present invention, the third manufacturing method produces functional layer 130 first and the region of the porous silicon subsequently. This has the disadvantage of requiring a wet-chemical process step after production of functional layer 130 so as to create the porous silicon. Figure 3a shows a substrate 100 by way of a superficial layer 101 made from thermal silicon. Substrate 100 according to the present invention is a silicon substrate, in particular. According to the present invention, functional layer 130 is provided above the thermal silicon-oxide layer, the former being patterned in a following step, which is shown in Figure 4b. After functional layer 130 has been created, the porous silicon region, which bears reference numeral 106, is produced in the third manufacturing method in Figure 3. In the process, so-called noses of substrate material, which is not part of porous region 106, are formed, specifically below the portions of functional layer 130 that are free-standing and denoted by reference numeral 131 in Figure 3. Such a nose, bearing reference numeral 99, can be seen in Figure 3c. In a subsequent step whose result is illustrated in Figure 3d, the region of porous silicon 106 from Figure 3c is removed with the aid of a wet-chemical process, and the free-standing region, which once again is denoted by reference numeral 108 in Figure 3, is produced. This region includes under-etched regions below functional layer 130, which bear reference numeral 135 in Figure 3d.

Figure 4 illustrates the result of the production of a micromechanical component of the present invention in accordance with the third manufacturing method according to the present invention as shown in Figure 3. Provided on substrate 100 is functional layer 130 as well as etched-out region 108 in which porous silicon layer 106 had been located earlier, which was used as sacrificial layer to produce the component according to the present invention. In Figure 4, functional layer 130 has a free-standing micro-bar, which is denoted by reference numeral 131 in the free-standing region. Shown through the micromechanical component according to the present invention is a sectional line AA along which the cross-sections illustrated in Figure 3 are provided. Visible in Figure 4 is under-etched region 135 recess 108. Since the production of porous silicon region 106 constitutes an isotropic process for the most part, so-called noses are formed below the free-standing structure, the noses bearing reference



numeral 136 in Figure 4. According to the present invention this is due to the fact that porous region 106 is produced after functional layer 130 has been created. The free-standing structure has poorer definition in the region of noses 136 than would be the case in a straight and defined transition between the region of functional layer 130 connected to substrate 100 to free-standing region 131 of functional layer 130.